FTD-HT-23-595-70

AD 714786

FOREIGN TECHNOLOGY DIVISION

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EDITED TRANSLATION

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English pages: 12

Source: Nalchik. Vysokogornyy Geofizicheskiy Institut. Trudy (Nalchik. Alpine Geophysical Institute. Transactions), No. 8, 1968, pp. 83-90.

Translated by: V. Mesenzeff/TDBRS-3

UR/3213-68-000-008

PREPARED BY:

TRANSLATION DIVISION
FOREIGN TECHNOLOGY DIVISION
WP-AFB, OHIO.

CALCULATION OF THE ATTENUATION COEFFICIENTS OF 0.6-14 μm WAVES PASSING THROUGH FOG

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Statement of the Problem

The aerosol (drops or bits of ice in precipitation and fog, smoke, and dust particles) is the basic variable part of the troposphere determining its optical properties in the visible and infrared areas of the spectrum. The composition, shape, and structure of the aerosol are the factors that determine the transparency of the atmosphere.

On the basis of physical presentations, the attenuation coefficient of electromagnetic waves, α 1/unit of length, can be presented as

$$\alpha = \alpha_s + \alpha_a + \alpha_p + \alpha_{aer}. \quad (1)$$

Here α_s is the coefficient of molecular scattering; α_a is the coefficient of molecular absorption; α_p is the attenuation coefficient caused by the radiation pressure (due to motion of drops or particles); α_{aer} is the coefficient of aerosol attenuation.

The coefficient of the molecular scattering for the visible portion of the spectrum is negligibly small. For example, for the wavelength $\lambda = 5500$ Å $\alpha \approx 0.012$ 1/km [1].

Molecular absorption in the windows of atmospheric transparency can also be disregarded [1].

The absorption and dispersion of waves of the optical band connected with the radiation pressure must be considered when the force of the pressure is sufficient to bring the water drops or particles in the atmosphere into motion. In their movement through air the drops (particles) generate friction, which is another cause for the attenuation of the field and the oscillation of the dipole moment in a unit volume of air caused by the motion of the drops will be another cause of scattering. According to work [2], the radiation pressure effect occurs only with very high radiating energies and small drops ($r > 1$ μm).

Thus, the effect of radiation pressure on the attenuation of the wave can be disregarded.

Consequently, the attenuation of waves of the optical range will be determined basically by the presence of aerosol in the atmosphere. From now on we will assume that $\alpha = \alpha_{aer}$.

This work is concerned with the calculation of the attenuation coefficient in mist and fog, using exact and approximate formulas of the scattering theory, and also with the comparison of the obtained results.

Determination of the Attenuation Coefficient in Mist and Fog Using Exact and Approximate Formulas

The attenuation coefficient of the electromagnetic oscillations, α dB/km, scattered in mist and fog can be calculated using the formula [3]

$$\alpha = 4.34 \cdot 10^{5} \int_{0}^{\infty} \sigma(m, \rho) N(r) dr. \quad (2)$$

Here $N(r)$ is the function of distribution of the drops with respect to size; $N(r)dr$ is the relative number of particles whose size is within the limits r, $r + dr$; σ(m and ρ) is the coefficient of attenuation on a spherical drop (unit of area); $m = n - j\kappa$ is the relative complex index of refraction on the water-air boundary; n is the index of refraction; κ is the absorption coefficient; $\rho = \frac{2\pi r}{\lambda}$ is the wave parameter; r is the radius of the drop; λ is the wavelength of the incident radiation.

Let us examine the values $\sigma(m, \rho)$ and N(r) which enter into expression (2). Experimentally it was established that the distribution curve N(r) of drops with respect to size in mist and fog is described well by the four-parameter family of functions [4 and 5]

$$N(r) = Ar^{\mu}e^{-\beta r^{\gamma}}, \tag{3}$$

where A is the normalization parameter; μ, β, and γ are curve parameters.

The four-parameter family of curves (3) is very general and permits us to describe with the necessary accuracy practically any single-apex distribution curve and, with summation of the expressions of type (3), also any multi-apex curve of distribution. Giving determined values to quantities μ and γ, we obtain the known distributions of the aerosols. For example, in 1930 I. Rokar proposed for the aerosol the distribution (3) with $\mu = 2$ and $\gamma = 1$:

$$N(r) = Ar^{2}e^{-\beta r}. \tag{4}$$

In 1952 H. Young found that in the surface layer [4]

$$N(r) = \frac{A}{r^4}, \tag{5}$$

in this case we have $\beta = 0$ and $\mu = -4$.

If we standarize distribution (4) to N – the number of particles in 1 cm^3 – we will obtain

$$A = N\frac{\gamma\beta^{\frac{\mu+1}{\gamma}}}{\Gamma\left(\frac{\mu+1}{\gamma}\right)}. \tag{6}$$

Then

$$N(r) = N \frac{\gamma \beta^{\frac{\mu+1}{\gamma}}}{\Gamma\left(\frac{\mu+1}{\gamma}\right)} r^{\mu} e^{-\beta r^{\gamma}}. \tag{7}$$

Here $\Gamma\left(\frac{\mu+1}{\gamma}\right)$ is the gamma-function from the argument $\frac{\mu + 1}{\gamma}$ and parameter β is determined by the expression

$$\beta = \left(\frac{\mu+1}{\gamma \bar{r}}\right)^{\gamma}, \tag{8}$$

where $\bar{r}$ is the average radius of the drop.

The majority of the experiments indicate that we can assume $\gamma = 1$. Parameters μ and $\bar{r}$ are given to describe the microstructures of the mist and fog.

The calculation of the coefficients of attenuation on a spherical drop $\sigma(m, \rho)$ can be accomplished using the exact and approximate formulas for scattering of light [3 and 6]. According to Mie's theory, the coefficient of attenuation on a spherical drop in air ($n = 1$ and $\kappa = 0$) is determined by expression [6]

$$\sigma(m, \rho) = \frac{\lambda^2}{2\pi} \operatorname{Im} \sum_{l=1}^{N} l(l+1)(-1)^l (c_l - b_l). \tag{9}$$

From (9) it is evident that the diffracted field is presented in the form of the sum of the individual partial waves (c_l – are electrical waves and b_l are magnetic waves). The intensity of excitation of the lth partial wave is determined by values c_l and b_l which depend essentially on ρ and on m.

In turn, the partial amplitudes c_l and b_l can be determined by the relationships

$$\begin{aligned} c_l &= i(-1)^l \frac{2l+1}{l(l+1)} \cdot \frac{\psi_l(\rho)\psi_l'(m\rho) - m\psi_l'(\rho)\psi_l(m\rho)}{\xi_l(\rho)\psi_l'(m\rho) - m\xi_l(\rho)\psi_l(m\rho)}, \\ b_l &= i(-1)^{l+1} \frac{2l+1}{l(l+1)} \frac{\psi_l'(\rho)\psi_l(m\rho) - m\psi_l(\rho)\psi_l'(m\rho)}{\xi_l'(\rho)\psi_l(m\rho) - m\xi_l(\rho)\psi_l'(m\rho)}. \end{aligned} \tag{10}$$

Coefficients c_l and b_l are determined by the cylindrical Bessel and Hankel functions with half-integer indexes. These functions are determined by the equations

$$\psi_l = \sqrt{\frac{\pi z}{2}} J_{l+1/2}(z), \quad \xi_l(z) = \sqrt{\frac{\pi z}{2}} H^{(2)}_{l+1/2}(z). \tag{11}$$

To determine the function $\xi_l(z)$, one of the relationships between the solutions of the Bessel equation is used:

$$\xi_l(z) = \psi_l(z) + i\chi_l(z), \tag{12}$$

where

$$\chi_l(z) = (-1)^l \sqrt{\frac{\pi z}{2}} J_{-(l+1/2)}(z) = -\sqrt{\frac{\pi z}{2}} Y_{(l+1/2)}(z). \tag{13}$$

To calculate functions $\psi_l(z)$ and $\chi_l(z)$ and their derivatives, we use the recurrence relationships of the type

$$\eta_{l+1}(z) = \frac{2l+1}{z}\eta_l(z) - \eta_{l-1}(z), \tag{14}$$

$$\eta_l'(z) = \eta_{l-1}(z) - \frac{l}{z}\eta_l(z). \tag{15}$$

When relationships (14) and (15) are used the initial functions are

$$\begin{aligned} \psi_0(z) &= \sin z; \qquad \psi_1(z) = \frac{\sin z}{z} - \cos z; \\ \chi_0(z) &= \cos z; \qquad \chi_1(z) = \sin z + \frac{\cos z}{z}; \end{aligned} \tag{16}$$

However, the calculation of functions $\psi_l(\rho)$, $\psi_l(\rho m)$, and $\xi_l(\rho)$ and their derivatives directly by recurrence relationships (14) and (15) leads to loss of accuracy for the large values of l. For example, if the values of functions $\psi_0(z)$, $\psi_1(z)$, $\chi_0(z)$, and $\chi_1(z)$ are known with an accuracy to 10^{-8}, then $\psi_l(z)$ and $\xi_l(z)$ with $\kappa > 0.1$ and $l = 80$-100 will have an accuracy up to 10^{-1}-10^{0}. The given problem was subjected to a detailed study. It turned out that for the direct calculation of function $\psi_l(m\rho)$ ($\rho \geq 50$; $n \leq 1.16$; $\kappa \geq 1.16$) with the aid of summing of the series [7]

$$\psi_l(m\rho) = \sqrt{\frac{\pi m\rho}{2}} J_{l+1/2}(m\rho) = \sqrt{\frac{\pi\rho m}{2}} \sum_{S=0}^{\infty} \frac{(-1)^S}{S!\Gamma(l+S+3/2)} \left(\frac{m\rho}{2}\right)^{l+2S+1/2} \tag{17}$$

a great deal of machine time would be required.

Consequently, the method of direct calculation of function $\psi_l(m\rho)$ using expression (17) is inappropriate.

For calculation of the function $\psi_l(m\rho)$, the so-called method of dispersion [8 and 9] was used; this ensures the calculation of the attenuation coefficient at large ρ and $\kappa > 0.1$ to four places. Such accuracy fully satisfies all practical questions.

In summing expression (9), the value of S was chosen thus: for $\rho = 0.5-1.5$, $S = 3$; for $\rho = 2-4$, $S = 5-7$; for $\rho = 8-12$, $S = 14-18$; and for $\rho \geq 13$, $S = (1.5-1.2)\rho$.

Calculation of the attenuation coefficient α is connected, as is indicated above, with great difficulties; moreover, calculations using formula (2) can only be accomplished by the numerical integration method.

The calculation of attenuation coefficients can be simplified considerably by using tables of light scattering [10]. However, the use of these tables does not eliminate the problem of using approximation formulas to calculate attenuation coefficients α.

The coefficient of attenuation on a drop of water, $\sigma(n, \rho)$, in the absence of absorption ($\kappa = 0$) is determined by [3]

$$\sigma(n, \rho) = \pi r^2 \left[2 - \frac{4}{x}\sin x + \frac{4}{x}(1 - \cos x)\right]. \tag{18}$$

Taking into account the absorption ($\kappa \neq 0$),

$$\sigma(m, \rho) = \pi r^2 \Big[2 - 4e^{-x \operatorname{tg} \nu} \frac{\cos\nu}{x^2} \sin(x - \nu) - \\ - 4e^{-x \operatorname{tg} \nu} \left(\frac{\cos\nu}{x}\right)^2 \cos(x - 2\nu) + 4\left(\frac{\cos\nu}{x}\right)^2 \cos 2\nu\Big]. \tag{19}$$

$$x = 2\rho\,(n-1), \qquad \operatorname{tg}\nu = \frac{\kappa}{n-1}.$$

Formulas (18) and (19) are valid with the following values: $n = 1.05\text{-}2$ and $(m-1) \leq 1$.

Substituting in expression (2) functions (7) and (18) or (19), we obtain the formula for the determination of attenuation coefficient α 1/km both in a nonabsorbing polydispersed sol

$$
\begin{gathered}
\alpha = \frac{\pi \beta^3 N \cdot 10^5}{\Gamma(\mu+1)} \sum_{i=1}^{4} I_i, \\
I_1 = \frac{2\Gamma(\mu+3)}{\beta^{\mu+3}}, \\
I_2 = -\frac{2}{c} \frac{\Gamma(\mu+2)}{[\beta^2 + (2c)^2]^{\frac{\mu+2}{2}}} \sin\left[(\mu+2)\operatorname{arc\,tg}\frac{2c}{\beta}\right], \\
I_3 = \frac{1}{c^2} \frac{\Gamma(\mu+1)}{\beta^{\mu+1}}, \\
I_4 = -\frac{1}{c^2} \frac{\Gamma(\mu+1)}{[\beta^2 + (2c)^2]^{\frac{\mu+1}{2}}} \cos\left[(\mu+1)\operatorname{arc\,tg}\frac{2c}{\beta}\right], \\
c = \frac{2\pi}{\lambda}(m-1),
\end{gathered} \tag{20}
$$

and in an absorbing polydispersed sol

$$
\begin{gathered}
\alpha = \frac{\pi \beta^3 N \cdot 10^5}{\Gamma(\mu+1)} \sum_{i=1}^{6} I_i, \\
I_1 = \frac{2\Gamma(\mu+3)}{\beta^{\mu+3}}, \\
I_2 = -\frac{4(\cos\nu)^2}{b} \cdot \frac{\Gamma(\mu+2)}{(b^2+q^2)^{\frac{\mu+2}{2}}} \sin\left[(\mu+2)\operatorname{arc\,tg}\frac{b}{q}\right], \\
I_3 = \frac{4\cos\nu\sin\nu}{b} \frac{\Gamma(\mu+2)}{(b^2+q^2)^{\frac{\mu+2}{2}}} \cos\left[(\mu+2)\operatorname{arc\,tg}\frac{b}{q}\right], \\
I_4 = -\frac{4(\cos\nu)^2\cos 2\nu}{b^2} \frac{\Gamma(\mu+1)}{(b^2+q^2)^{\frac{\mu+1}{2}}} \cos\left[(\mu+1)\operatorname{arc\,tg}\frac{b}{q}\right], \\
I_5 = -\frac{4(\cos\nu)^2\sin 2\nu}{b^2} \frac{\Gamma(\mu+1)}{(b^2+q^2)^{\frac{\mu+1}{2}}} \sin\left[(\mu+1)\operatorname{arc\,tg}\frac{b}{q}\right], \\
I_6 = \frac{4(\cos\nu)^2\cos 2\nu}{b^2} \frac{\Gamma(\mu+1)}{\beta^{\mu+1}}, \\
b = \frac{4\pi}{\lambda}(n-1), \quad l = b\,\operatorname{tg}\nu, \quad q = l + \beta.
\end{gathered} \tag{21}
$$

Comparison of the Attenuation Coefficients in Mist and Fog Calculated by Exact and Approximate Formulas of Light Diffusion

Comparative calculations (see Table 2) were made for several operating waves of a laser which lie in the spectral windows of atmospheric transparency [11].

The optical properties of liquid water for the selected laser emission waves were obtained by the graphic interpolation of data presented in works [6, 12]. These works give values of n and κ up to $\lambda < 9$ μm at $t = 20°C$ and for $\lambda > 9$ μm at $t = 18°C$.

On the basis of the experimental data on the microstructure of the mist and fog the following values for the radii of drops were selected: 0.2 (0.2) 1 (0.4) 5 (0.5) 14 (2) 60 (number in parentheses – step of calculation), and the mean drop radii were: 1 (mist) 2, 3, 5, 7, 10, and 15 μm. The given drop sizes basically characterize the microstructure of dense mist and fog.

The attenuation coefficients for the mist and fog per 1/km were determined with the condition that the concentration of drops $N = 1$ in 1 cm^3 of air.

To determine the effect of the parameter μ on the attenuation coefficient, a numerical experiment was carried out on the wavelength $\lambda = 0.63$ μm of emission of a He–Ne laser; the optical constants of the water – air medium were $n = 1.3318$; $\kappa = 0$.

The calculations were done by the formula

$$\alpha = 10^{5} \sum_{1}^{56} \sigma(m, \rho) N(r) \Delta r, \qquad (22)$$

taking into account expression (9) and distributions (7) for μ equaling 0, 2, 4, 6, 8, 10, and 20.

The tabulated values of α for 1 km are presented in Table 1.

Table 1

$\bar{r}$ μm	λ=6328 Å; n=1,3318; κ=0						
	μ=0	μ=2	μ=4	μ=6	μ=8	μ=10	μ=20
1	1,405 −2	9,700 −3	8,744 −3	8,257 −3	7,923 −3	7,661 −3	6,811 −3
2	5,359 −2	3,679 −2	3,335 −2	3,188 −2	3,108 −2	3,056 −2	2,936 −2
3	1,168 −1	8,101 −2	7,341 −3	7,018 −2	6,842 −2	6,732 −2	6,508 −2
5	3,164 −1	2,168 −1	1,985 −1	1,901 −1	1,851 −1	1,819 −1	1,746 −1
7	6,166 −1	4,135 −1	3,754 −1	3,620 −1	3,551 −1	3,505 −1	3,397 −1
10	1,204	8,324 −1	7,413 −1	7,033 −1	6,837 −1	6,726 −1	6,588 −1
15	2,235	1,893	1,696	1,601	1,544	1,505	1,406

Note. Here and in Table 2, the fifth number, separated from the preceding by spacing, designates the coefficient on base ten by which the four digital number preceding it will be multiplied.

The variation of the attenuation coefficient in fogs as a function of parameter $\mu = 2-20$ does not exceed 20%, which indicates that the effect of the parameter μ on the quantity α is small. If on the basis of [3] we assume that $\mu = 6-8$, then in this case with variation of μ from 2 to 8, α will not vary more than 10-15%.

In calculating attenuation coefficients in mist and fog it was assumed that $\mu = 2$ and $\bar{r}$ equaled μm 1, 2, 3, 5, 7, 10, and 15.

The use of distribution with $\mu = 2$ is justified by our effort to obtain a certain reserve coefficient during the determination of the range of action of optical means of communication and location.

Table 2 shows the values of the polydispersing attenuation coefficients α_{pr} calculated by the approximate formulas (20) and (21) with $N = 1$ per 1 cm^3 of air.

The data of Table 2 shows that the error in the determination of the attenuation coefficients using approximate formulas does not exceed ~18% in comparison with the calculation results obtained by the exact formulas; this is entirely acceptable for carrying out engineering calculations.

Table 2

λ μm	n	$\varkappa$	$\bar{r}$ мкм	α 1/км	α_{pr} 1/km	Relative error %
0,6328	1,3318	0	1	9,700 —3	9,203 —3	5,1
			2	3,679 —2	3,590 —2	2,7
			3*	3,101 —2	7,820 —2	3,4
			5	2,162 —1	2,199 —2	5,0
			7	4,135 —1	4,341 —1	6,4
			10	8,324 —1	8,855 —1	5,5
			15	1,993	1,997	1,4
1,0621	1,3247	$2{,}8\cdot10^{-6}$	1	1,063 —2	1,024 —2	3,7
			2	3,853 —2	3,430 —2	11,6
			3	8,360 —2	7,520 —2	10,6
			5*	2,224 —1	2,025 —1	9,0
			7	4,247 —1	3,994 —1	5,4
			10	8,693 —1	8,218 —1	5,5
			15	1,999	1,852	7,4
2,09514	1,302	$1{,}25\cdot10^{-3}$	1	1,069 —2	8,797 —2	17,8
			2	4,556 —2	3,900 —2	14,3
			3	9,237 —2	7,980 —2	13,2
			5	2,345 —1	2,199 —1	6,3
			7	4,379 —1	4,341 —1	0,9
			10*	8,714 —1	8,855 —1	1,6
			15	1,945	1,990	2,4
3,9806	1,349	$6{,}15\cdot10^{-2}$	1	6,250 —3	6,019 —3	3,7
			2	4,762 —2	3,895 —2	18,2
			3	1,060 —1	9,417 —2	11,2
			5	2,545 —1	2,315 —1	9,0
			7	4,623 —1	4,456 —1	3,6
			10	9,661 —1	8,913 —1	1,6
			15	2,005	1,997	6,4
10,6324	1,173	$8{,}23\cdot10^{-2}$	1	1,031 —2	9,839 —4	4,5
			2	1,004 —2	9,203 —3	8,4
			3	3,593 —2	3,565 —2	0,9
			5	1,560 —1	1,505 —1	4,7
			7	3,768 —1	3,588 —1	4,8
			10	8,793 —1	8,566 —1	1,7
			15	2,098	2,048	2,4
12,913	1,262	0,281	1	2,504 —3	2,350 —3	6,0
			2	2,000 —2	2,100 —2	5,0
			3	6,005 —2	5,625 —2	6,3
			5	2,074 —1	4,852 —1	10,7
			7	4,302 —1	3,993 —1	7,2
			10	9,050 —1	8,624 —1	4,7
			15	2,064	1,997	3,2

Note. The asterisk denotes the $\bar{r}$ values after which the calculations of α were carried out with less accuracy.

Figure 1 shows the ratio of the attenuation coefficients of various wavelengths in mist and fog to the attenuation coefficient for the wavelength λ = 0.6328 μm.

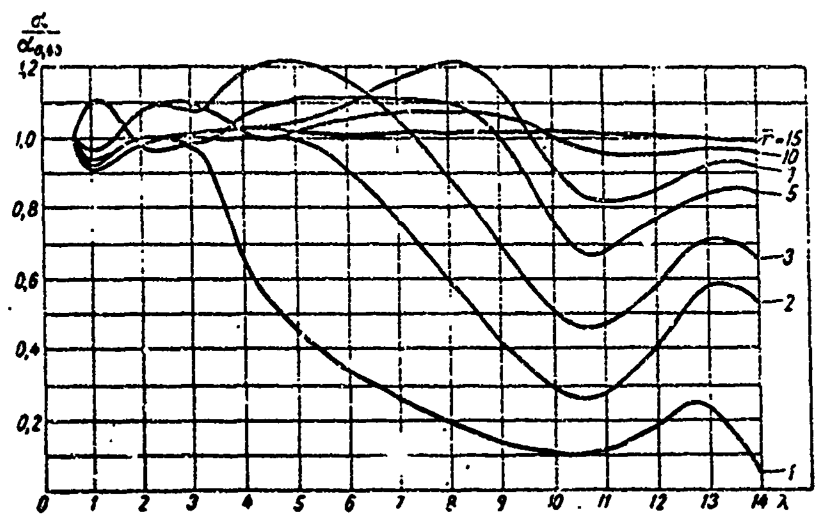

Fig. 1

The direct measurement of the quantity of drops in mist and fog is a tedious operation and does not permit fast calculation of the attenuation coefficient. At the same time, with the aid of radars the water content of fog located any place along the route can be determined from a distance. For this reason in work [13] the relationships connecting the attenuation coefficient with the water content of the fog were obtained.

Conclusions

1. The results of calculations using the approximate and exact formulas coincide with an accuracy of up to 20%.

2. In the range 0.6-14 μm, electromagnetic waves in the 10-12 μm region pass through fog with the least attenuation.

3. In heavy, optically dense fogs (for short λ) the coefficient of attenuation is not selective.

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UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)
Foreign Technology Division
Air Force Systems Command
U. S. Air Force

2a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

2b. GROUP

3. REPORT TITLE
CALCULATION OF THE ATTENUATION COEFFICIENTS OF 0.6-14 mu m WAVES PASSING THROUGH FOG

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Translation

5. AUTHOR(S) (First name, middle initial, last name)
Zel'manovich, I. O.; Lobkova, L. M.; and Milyutin, Ye. R.

6. REPORT DATE
1968

7a. TOTAL NO. OF PAGES
12

7b. NO. OF REFS
13

8a. CONTRACT OR GRANT NO.

b. PROJECT NO.

c.

d. DIA Task No. T70-05-03

9a. ORIGINATOR'S REPORT NUMBER(S)
FTD-HT-23-595-70

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT
Distribution of this document is unlimited. It may be released to the Clearinghouse, Department of Commerce, for sale to the general public.

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
Foreign Technology Division
Wright-Patterson AFB, Ohio

13. ABSTRACT

Precise and approximate equations are derived for use in determining the coefficient of attenuation alpha 1/km of electromagnetic waves in mists and fogs. The simplified equations are given in unabsorbed polydispersed aerosols and absorbed polydispersed aerosols. Comparative calculations were made for several laser wavelengths in the spectral windows of atmospheric transparency. The optical properties of the water drops used as sols, droplet sizes used, and the mean droplet radii were given. Results obtained in a given calculation using a M-20 electronic computer and those obtained in using given equations are tabulated. They indicate that the use of these approximate equations results in errors which are only about 18 percent larger than those derived from precise and tedious equations. Electromagnetic waves in the 10-12 mu spectra passed through fogs with minimal attenuation. In heavy, optically dense fogs (for short wavelengths) the coefficient of attenuation was not selective. Orig. art. has: 1 figure, 2 tables, and 22 formulas. [AT8032281]

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Atmospheric Optics						
Fog						
Mist						
Visible Spectrum						
Electromagnetic Wave						
Laser						